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Parton Distributions with High Energy Proton Beams

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PARTON DISTRIBUTIONS WITH HIGH ENERGY PROTON BEAMS

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The opportunities for using high energy proton beams to advance our current knowledge in parton distributions are discussed. Highlights from some Fermilab dimuon production experiments with 800 GeV proton beams are presented. Possible future directions are discussed.

1 Introduction

The parton substructures in the nucleons and nuclei were first discovered in electron Deep Inelastic Scattering (DIS) experiments at SLAC. During the last 30 years, DIS experiments using high energy electron, muon, and neutrino beams have provided much information on the parton structure functions. Extensive efforts have focussed recently on the study of spin-dependent structure functions using polarized electron and muon beams, as well as the behavior of parton structure functions at very small Bjorken-x region in electron-proton collision at HERA.

Lepton-pair production in hadron-hadron interactions offers an independent and often unique means for studying parton distributions. In this paper, I will first discuss recent Fermilab experiments to illustrate the advantages of this experimental tool. I will then discuss some of the important un-resolved issues in parton distributions and how the lepton-pair production experiments at existing and future facilities, including the Japan Hadron Project (JHP), could help to clarify these issues.

2 Lepton-Pair Production as a Tool for Parton Distributions

Studies of high-mass lepton pairs produced in hadron-hadron interactions have led to many important discoveries. It was through the detection of di-leptons that the J/Ψ, Υ, and Z° particles were first observed. The Drell-Yan process, which in its simplest form involves annihilation of quark and antiquark into a virtual photon, accounts for the continuum in the di-lepton mass spectra. The mechanisms of the Drell-Yan process are quite well understood and indeed this process has been used for QCD tests.

As a tool to study parton distributions, the Drell-Yan process offers several distinct advantages. First, the parton distributions in unstable mesons and hyperons could only be deduced from Drell-Yan experiments using meson or hyperon beams. Such information could not be obtained in DIS experiments. Indeed, the current knowledge on pion and kaon structure functions are entirely due to the Drell-Yan process. Second, the flexibility in the choice of beam type and the kinematical regions allows one to single out a specific component in the parton distributions for studies. For instance, an antiproton beam could be used to probe the quark contents of the target nucleons, while a proton beam can be used to study the antiquark distributions in the target nucleons. Third, the polarized Drell-Yan exepriments could probe both the sea-quark helicity distributions and the chiral-odd quark structure functions, which could not be obtained in the polarized DIS experiments.

Despite much theoretical and experimental efforts, our current knowledge on parton distributions in the nucleons is still far from complete. This situation is well reflected by the many 'surprises' discovered in the last 15 years in DIS experiments. The first surprise came from the EMC collaboration when the structure functions of a nuclear target (iron) were found[1] to be significantly different from that of a light nucleus (deuterium). This famous 'EMC' effect provided the first unambigious evidence that the parton distributions in the nucleon are modified in the nuclear environment. The second surprise is the so-called 'spin crisis' deduced from polarized DIS experiments[2] which suggested that only a small fraction of the proton spin is carried by the quarks and antiquarks. The third surprise was from the NMC collaboration[3] in a measurement of the 'Gottfried Sum'[4]. The NMC experiment showed that the Gottfried Sum deviated significantly from the expected value suggesting that the u and d sea-quark distributions in the nucleon are different. These DIS results prompted a series of Fermilab experiments and some future proposals aimed at sheding new light on the origins of these puzzles. In the next section, the highlights of the Fermilab experiments will be presented.

3 Nuclear Dependence of the Parton Distributions

Following the discovery of the EMC effect many theoretical models were proposed to explain the apparent modifications of parton distributions in nuclei. The proton-induced Drell-Yan process offers the advantage to probe selectively the antiquark distributions in the nuclei. The expression for the Drell-Yan cross section is

$$\frac{d^2\sigma}{dx_1 dx_2} = K(\frac{4\pi\alpha^2}{9M^2}) \sum_i e_i^2 (q_i^B(x_1)\overline{q}_i^T(x_2) + \overline{q}_i^B(x_1) q_i^T(x_2)), \tag{1}$$

where $q_i, \bar{q}_i$ are the structure functions for quark and antiquark of flavor i (for simplicity, the Q^2 dependence of the structure functions is not explicitly shown). x_1 and x_2 are the fractions of the momenta of the beam (B) and target (T) hadrons carried by the quark and antiquarks. M is the mass of the dimuon and e_i is the quark charge. The factor K takes into account the contributions from higher order diagrams. It is recalled that the $F_2(x)$ measured in DIS experiments is given as

$$F_2(x) = \sum_i e_i^2 x(q_i^T(x) + \overline{q}_i^T(x)). \tag{2}$$

From Eqs. (1) and (2), the Drell-Yan process appears to be more complicated than the DIS, since it involves two combinations of the structure functions from the beam hadron and the target hadron. Nevertheless, at the kinematic region of $x_1 > 0.2$ and $x_F > 0.1$ ($x_F = x_1 - x_2$), the second term in Eq. (1) has negligible contribution and to a very good approximation the proton-induced Drell-Yan cross section is proportional to

$$\sum_i e_i^2 q_i^B(x_1)\overline{q}_i^T(x_2). \tag{3}$$

Unlike the DIS process which is sensitive to both the quark and the antiquark distributions, the proton-induced Drell-Yan process probes only the antiquarks in the target nuclei. Therefore, an accurate measurement of the nuclear dependence of the Drell-Yan cross section would be sensitive to any possible variation of antiquark distributions from nucleon to nuclei.

Prior to the E772 experiments, several proton-induced and pion-induced Drell-Yan experiments[5,6] have been performed to study the nuclear effects. Although the results were consistent with a linear nuclear dependence, the statistical accuracies of these experiments were relatively low. Furthermore, due to the presence of valence quark and antiquark in the beam, the pion-induced Drell-Yan process[6] does not selectively probe the antiquark distributions in the target nuclei.

In the E772 experiment, approximately 0.6×10^6 dimuon events with $9\ GeV \geq M_{\mu^+\mu^-} \geq 4\ GeV$ or $M_{\mu^+\mu^-} \geq 11\ GeV$ have been collected from 800 GeV proton interacting on liquid deuterium and solid C, Ca, Fe and W targets. The spectrometer covers the kinematic range $x_F \geq 0.0$ and $x_2 \geq 0.04$. The nuclear dependence of the integrated Drell-Yan cross sections measured in E772 is well described by $A^{0.998 \pm 0.002}$, where A is the mass of the target nucleus. The absence of any enhancement of antiquark distribution at small x in heavy nuclei is in striking contrast to the predictions of the pion-excess models[7] and an early version of the quark-cluster model[8]. The data are in good agreement with the rescaling model[9] and a later version of the quark-cluster model[10]. The E772 data[11] set a stringent limit on the magnitude of nuclear effect of antiquark distributions.

The E772 data showed a hint of the shadowing effect at the smallest x_2 ($x_2 = 0.04$). It would be very useful to extend the Drell-Yan measurement to even lower x_2, say, $x_2 = 0.01$, where very pronounced shadowing effects were observed[12,13] in DIS. Recalling that ${M^2}_{\mu^+\mu^-} = Sx_1x_2$, there are two ways to reach the very low x_2 region. One could either go to much higher energies, possible at the heavy ion collider at RHIC, or study dimuons at lower masses ($4\ GeV \geq M_{\mu^+\mu^-} \geq 2\ GeV$). The Drell-Yan yields at low masses are quite large, but some cautions are needed to separate the Drell-Yan process from the $J/\psi(\psi')$ production, as well as to determine the contributions from charm decays. The feasibility to extend the Drell-Yan measurements to smaller mass will be explored in the Fermilab experiment E866.

Several authors have considered the effects of initial-state interaction in the Drell-Yan process[14,15]. Multiple-scattering of partons will broaden the dimuon transverse momentum (P_T) distributions for interaction on a heavy nucleus. Such effect is indeed observed in the E772 experiment[11], as well as in the NA10 experiment[6] for 140 and 280 GeV pion beams, and it can be quantitatively explained by the multiple scattering model[15]. Another possible effect of the initial-state interaction is to reduce the longitudinal momentum (x_F) of the dimuons. In fact, it has been suggested[16] that the nuclear effects at small x_2 observed in E772 can be understood by the energy-loss mechanism. However, the amount of energy loss needed to explain the data appears unrealistically high[17]. It is likely that the observed Drell-Yan nuclear dependence contain both the initial-state interaction effect, which is a function of x_F, and the nuclear structure function effect, which depends on x_2. Future data to extend the measurements to smaller x_2 values and to higher energies will help to disentangle these two effects.

In addition to the small x_2 region discussed earlier, the large x_2 region is also interesting. The suppression of the parton densities in nuclei at moderately large $x_2 (x_2 > 0.2)$, as observed in the DIS experiments, still need to be confirmed by the Drell-Yan experiments.

4 Flavor Dependences of the Parton Distributions

The flavor dependences of the sea quarks in the proton are not well determined. It was assumed by many authors that the $\bar{u}$ and $\bar{d}$ sea quark distributions are identical in the proton. It came as a surprise when the NMC collaboration reported[3] a measuremnet of the Gottfried Sum, showing evidence that $\bar{u} \neq \bar{d}$

in the proton. The Gottfried Sum is defined as $I_G(x_1 \rightarrow x_2) = \int_{x1}^{x_2}(F_2^p(x) - F_2^n(x))/xdx$. Assuming isospin symmetry in the nucleons and $\bar{u} = \bar{d}$ in the proton, it can be shown straightforwardly that $I_G(0 \rightarrow 1) = 1/3$, called the Gottdried Sum Rule (GSR)[4]. Early SLAC data[18] gave $I_G(0.02 \rightarrow 0.8) = 0.20 \pm 0.04$, indicating that GSR could be violated. Indeed, these data had prompted Field and Feynman[19] to suggest that Pauli-blocking effect causes suppression of the gluon $\rightarrow u\bar{u}$ process relative to the gluon $\rightarrow d\bar{d}$ process, hence $\bar{d} > \bar{u}$ in the proton.

The NMC collaboration[3] extended the measurement of I_G to small x region. By extrapolating the experimental result $I_G(0.004 \rightarrow 0.8) = 0.221 \pm 0.008 \pm 0.019$ to the unobserved x region, NMC obtained $I_G(0 \rightarrow 1) = 0.235 \pm 0.026$, significantly lower than the value of 1/3 given by GSR.

Many explanations have been proposed for the apparent violation of GSR. Martin et al.[20] suggested that an unusually large contribution to the Gottfried Sum can come from $x < 0.004$ such that GSR is not violated. The MRS parametrization gives $I_G(0 \rightarrow 0.004) = 0.10$ and $F_2^n/F_2^p < 1$ as $x \rightarrow 0$. It is interesting that recent E665 result[21] indeed show that $F_2^n/F_2^p < 1$ over the wide range of $10^{-6} \leq x \leq 0.3$. Unfortunately, the Q^2 values are very small in E665. It would be very desirable to measure F_2^n/F_2^p at small x and large Q^2, perhaps at the HERA collider.

Another interesting explanation was offered by Ma[22], who pointed out that charge-symmetry-breaking (CSB) effect could contribute to the apparent violation of GSR. However, an 8% CSB effect, integrated over the entire x region, is required. This large amount of CSB is inconsistent with the smaller CSB effects observed in other processes. Nevertheless, it is plausible that CSB could contribute partially to the violation of GSR. Londergan et al.[23,24] also predicted a surprisingly large CSB effect, up to $\sim 10\%$ at $x \sim 0.7$, for the proton valence quark distributions. It would be very interesting to identify the CSB effects at the parton level. Several experiments to look for such effects have been suggested.[22,23]

Many authors consider the NMC result as evidence for an asymmetric $\bar{u}, \bar{d}$ distributions in the proton. Using the NMC result for I_G and assuming no CSB effect, one obtains $\int_0^1(\bar{d}(x) - \bar{u}(x))dx = 0.14 \pm 0.02$, showing an excess of $\bar{d}$ over $\bar{u}$ in the proton. What are the mechanisms which would lead to $\bar{d} > \bar{u}$ in the proton? As mentioned earlier, the Pauli-blocking effect favors $\bar{d}$ over $\bar{u}$. Unfortunately, it is difficult to make quantitative calculations. Another mechanism, advocated by many authors,[25] invokes the pion cloud in the proton. In this so-called 'Sullivan process', the π^+ in $p \rightarrow n + \pi^+$ would contribute to an excess of $\bar{d}$. Detailed calculations taking into account both the $p \rightarrow n + \pi^+$ and the $p \rightarrow \Delta^{++} + \pi^-$ processes show that $\sim 50\%$ of the observed GSR violation is accounted for[25]. Using a Generalized Sullivan process, which also contains the $N \to K + Y$ processes, Hwang and Speth[25] were able to explain the NMC data well.

It should also be mentioned that Bourrely and Soffer[26] speculated on the possible link between the $\bar{d}/\bar{u}$ asymmetry and the proton spin. In particular, they wrote down the Ansatz : $\Delta\bar{u}(x) = \bar{u}^{\uparrow}(x) - \bar{u}^{\downarrow}(x) = \bar{u}(x) - \bar{d}(x)$. Since $-1 \leq \Delta\bar{u}/\bar{u} \leq 1$, this Ansatz implies $\bar{d}(x)/\bar{u}(x) \leq 2$. A test of the Bourrely and Soffer's model as well as many other models which predict $\bar{d}/\bar{u}$ asymmetry could be made by measuring the $\bar{d}(x)/\bar{u}(x)$ as a function of x. It should be noted that the GSR measurements only give information on the integral of $\bar{d}(x) - \bar{u}(x)$.

It has been proposed that the Drell-Yan process provides an independent and sensitive test of the possible $\bar{u}/\bar{d}$ asymmetry in the proton[27]. In fact, the E772 Drell-Yan data obtained with tungsten and isoscalar targets have been compared[28] with predictions from various models. More recently, the NA51 experiment reported[29] $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d) = 0.91 \pm 0.02 \pm 0.02$ measured at 450 GeV near $x_F \simeq 0$ and $x = 0.18$, showing a large asymmetry of $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ in the proton. The E866 experiment at Fermilab is designed to measured the ratio $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d)$ over a wide x range $(0.05 < x < 0.3)$ at 800 GeV and it should provide a definitive test for the various models.

In addition to the DIS and the Drell-Yan processes, J/ψ and Υ production could also be sensitive to the sea-quark distributions in the nucleon. Using the semi-local duality model and the lowest-order QCD cross sections for the $q\bar{q}$ annihilation and the gg fusion processes, the sensitivity of the proton-induced J/ψ and Υ production to the possible $\bar{u}/\bar{d}$ asymmetry has been studied[30]. The ratio $R(x_F)$, defined as

$$R(x_F) = 2\ \frac{d\sigma/dx_F\ (p+p \to J/\psi(\Upsilon))}{d\sigma/dx_F(p+d \to J/\psi(\Upsilon))} \tag{4}$$

would be equal to 1 for all models which assume $\bar{u} = \bar{d}$. On the other hand, $R(x_F)$ could deviate significantly from 1 if $\bar{u} \neq \bar{d}$, especially at large x_F where $q\bar{q}$ annihilation has a dominant contribution. A more detailed discussion can be found in Ref. 30.

The opportunity to study $p+p$ and $p+A$ collisions at the future heavy ion collider, RHIC, suggests yet another process, namely the production of W and Z bosons, which is sensitive to the $\bar{u}/\bar{d}$ asymmetry. An interesting quantity to be considered is the ratio of the differential cross sections for W^+ and W^- production. It is shown in Ref. 31 that W production in $p+p$ collision at RHIC could provide a sensitive measurement of the $\bar{u}/\bar{d}$ asymmetry.

5 Future Prospects

In this section I will list some possible directions for future Drell-Yan experiments.

5.1 Mechanisms of Drell-Yan and QCD tests

In the LO Drell-Yan process, the virtual photons are transversly polarized and the angular distribution for $\gamma^* \to \mu^+\mu^-$ decay follows a simple $1 + cos^2\theta$ form. The NLO diagrams for Drell-Yan, which contain an additional gluon line, will modify the decay angular distributions[32]. There exists QCD predictions for the θ and ϕ distributions, but the relevant proton-induced Drell-Yan data are still lacking. A high-statistics Drell-Yan experiment with large acceptance in the decay angles would be highly desirable.

A peculiar behavior of the pion-induced Drell-Yan process was observed[33] at large $x_F (x_F \to 1)$, where the dimuons were produced with longitudinal polarization rather than the expected transverse polarization. Higher-twist effect was invoked to explain[34] the pion data. No data yet exist for proton-induced Drell-Yan polarization at $x_F \to 1$. As shown in the FNAL E789 experiment[35], detection of dimuons produced in the beam dump could provide a means to measure the very small Drell-Yan cross sections at large x_F.

The UA1 collaboration reported[36] the measurements of high P_t low-mass dimuon events at $S^{1/2} = 630GeV$. It was shown[37] that the mechanisms for producing high P_t dimuons are closely related to that of direct-photon production. It would be very interesting to confirm this at fixed-target energies. If the relation between high-P_t Drell-Yan and direct photon production holds for a wide range of energies, then the measurement of low-mass high-P_t dimuons provides an alternative to the more difficult measurement of direct-photon production. An interesting implication is that the dimuon data could be used to deduce the gluon structure functions, similar to what was done in the direct-photon production experiments.

5.2 Symmetries in the parton distributions

The E866 experiment will soon provide a high statistics mesurement of $p+d/p+p$ Drell-Yan ratios and the question whether the sea-quark distributions in the proton is up/down symmetric will be resolved soon. However, the results will be subject to the uncertainties caused by the nuclear effects associated with the use of deuterium target, and by the unknown contributions from charge-symmetry breaking effect. As discussed earlier, the W-production asymmetry in $p+p$ collision is free from these two problems and should be studied at the RHIC collider[31].

Compared to the up/down sea-quarks, the strange quark content in the proton is very poorly known. Neutrino-induced charm production experiments showed that the strange quark content is roughly 40 percent of the lighter up and down sea-quarks. Recent studies[38] showed that the s and $\bar{s}$ distributions in the proton could have very different shapes, even though the net amount of strangeness in the proton vanishes. By comparing the ν and $\bar{\nu}$ induced charm production in a NLO analysis, the CCFR collaboration[39] concluded that the s and $\bar{s}$ distributions are very similar. However, the reliability of extracting the strange quark distributions in the NLO analysis is still being disputed[40]. Drell-Yan experiments using $K^\pm$ beams might provide an independent determination of the $s/\bar{s}$ ratios in the proton. A possible method is simply to measure the $K^+ + p/K^- + p$ Drell-Yan cross section ratios.

Recent analysis[41] of proton and deuteron deep-inelastic scattering data have suggested that the extracted d/u quark distribution ratio at large x may be significantly larger than previously believed, provided that the data are corrected for nuclear binding effects in the deuteron. In particular, the analysis in Ref. 41 suggested that as $x \to 1$ the value of d/u approaches 1/5[42], significantly different from the value of 0 deduced from earlier analysis. Given the sensitivity of the d/u ratio to theoretical treatments of the binding effects in the deuteron, one would obviously like to appeal to data without the need to model the nuclear effects in the deuteron. One such possibility is through W-boson production in $p\overline{p}$ and pp collisions[43]. Another possiblity is to measure the $\pi^+ + p/\pi^- + p$ Drell-Yan cross section ratios at the kinematic regions corresponding to large values of x_1 and x_2.

5.3 Parton distributions in unstable hadrons

As mentioned earlier, the Drell-Yan process provides a unique tool to study parton distributions in unstable hadrons such as pions, kaons and hyperons. Up to now, pion beam has been used in several Drell-Yan experiments. Very little data exist for kaon beam, and no attempt was made to use hyperon beams. The kaon-induced Drell-Yan data indicated that the strange valence quark has a harder distribution than the non-strange valence quark, but more precise data are needed. The difference between the pion and kaon parton distributions could give insight for the breaking of SU(3) at the parton level. A comparison between the hyperon and nucleon structure functions provides similar information for the baryon sector[44]. Considering the relatively low intensity for the kaon and hyperon beams, it is necessary to design an experiment using thick targets and with large solid angle acceptance. It should be noted that rather intense Σ and Ξ beams are currently being used at Fermilab for the SELEX and HyperCP experiments.

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